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FROSTY, FREEZING AND SEVERE FREEZING DAYS AND THEIR SYNOPTIC IMPLICATIONS IN MAŁOPOLSKA, SOUTHERN POLAND, 1951–2000

Abstract: This study discusses the occurrence of days with unique thermal characteristics for the period 1951–2000. The authors investigated long-term variability, probability of occurrence and synoptic conditions favourable to frosty ($t_{min} \leq 0^{\circ}C \wedge t_{max} > 0^{\circ}C$), freezing ($t_{max} < 0^{\circ}C$) and severe freezing ($t_{max} < -10^{\circ}C$) days at six stations in the southern part of Poland. The occurrence of frosty days is characterized by the highest diversity, both in spatial and temporal terms and these days depend on the landform to the highest degree. The number of freezing days ranged from 28–30 in the foothills of the Carpathians to 147 at 2000 m a.s.l. in the Tatra Mountains, with severe freezing days from ca. 2 to ca. 18 days respectively, though no distinct trends were noted in their long-term progression. The anticyclonic situations and air mass advection from the southern sector (frosty days), from the east, south-east and north (freezing and severe freezing days) were the most favourable for the days examined.

Key words: frosty days, freezing days, severe freezing days, climate change, synoptic situations, Małopolska.

Introduction

Contemporary lifestyles in many societies, where most time is spent indoors or on motorised transport, has greatly reduced physical exercise and made our bodies more vulnerable to exposure. In this context the occurrence of weather conditions regarded as oppressive to the human body has shifted from the individual to the community scale.

Certain air-temperature conditions are among the factors with an adverse influence on the human body, potentially making everyday life more difficult. Scientifically these have normally been dealt with in terms of the occurrence and variability of extreme temperatures on seasonal, annual or long-term scales (Karl et al. 1993; Brázdil et al. 1996; Easterling et al. 1997, 2000; Trepińska & Kowanetz 1997; Piotrowicz 1999, 2002/2003; Brunetti et al. 2000; Niedźwiedź 2000a; Wibig & Głowicki 2002; IPCC 2007). Recently, however, increasing attention has been devoted to the occurrence of days with temperatures regarded as strongly stimulating. These are days when the temperature exceeds certain identified threshold values and has a considerable influence on the functioning of the human body, as well as on the course of other weather processes. Investigation of this area involves the identification of periods with the highest frequency of such days as well as heatwaves or cold waves, and the description of individual events (Hess 1965; Trepińska 1975; Hess et al. 1989; Limanówka 1991, 1999; Morawska-Horawska 1991; Mroczka 1992; Niedźwiedź et al. 1996; Kozłowska-Szczęsna et al. 1997; Cebulak 1999; Folland et al. 1999; Nicholls & Murray 1999; Piotrowicz 1999, 2002/2003, 2007; Kossowska-Cezak 2003; Trepińska et al. 2005). Additionally, efforts have been made to establish relationships between days with characteristic temperature and atmospheric circulation, in order to help us understand and forecast their long-term trends (Niedźwiedź & Ustrnul 1994; Domonkos et al. 2003; Piotrowicz 2007).

The main aim of this study is to determine the occurrence patterns of days with special air temperature characteristics in Małopolska (southern Poland) between 1951 and 2000. These were investigated in terms of long-term variability and seasonal probability of occurrence, as well as in relation to the synoptic conditions favourable for their occurrence.

Methodology and materials

The study involves maximum and minimum temperature records from six weather stations located in southern Małopolska (Kraków, Tarnów, Nowy Sącz, Aleksandrowice, Zakopane and Kasprowy Wierch – Table 1, Fig. 1), as well as a calendar of synoptic situation types developed by Niedźwiedź for the area over the Upper Vistula River Basin. The data were taken from

Table 1. Stations used in the study

Station	WMO number	Latitude	Longitude	Altitude [m a.s.l.]	Terrain form	Location
Kraków	12 566	50°05'N	19°48'E	237	concave	Vistula valley -Krakowska Gate
Tarnów	12 575	50°02'N	20°59'E	209	convex	Tarnowski plateau
Aleksan-drowice	12 600	49°48'N	19°00'E	398	convex	Beskid Mały Mountain
Nowy Sącz	12 660	49°37'N	20°42'E	295	concave	Sądecka Basin
Zakopane	12 625	49°18'N	19°57'E	857	concave	Zakopiańska Basin
Kasprowy Wierch	12 650	49°14'N	19°59'E	1989	convex	Tatra Mountain – summit

Fig. 1. Location of weather stations

the daily weather bulletins (*Codzienny Biuletyn Meteorologiczny*) of IMGW (the Polish weather service: Institute of Meteorology and Water Management) published in the period 1951–2000. The bulk of the analysis is devoted to the identification of thermally characteristic days, using generally accepted criteria, and to examining their long-term variability. The characteristic days investigated here included frosty days ($t_{min} \leq 0°C \wedge t_{max} > 0°C$), freezing days ($t_{max} < 0°C$) and severe freezing days ($t_{max} < -10°C$).

The seasonal analysis uses a popular seasonal breakdown into winter (December to February), spring (March to May), etc. In the second section, the occurrence of characteristic days which has been identified is compared to the accompanying synoptic situations. To select the situations most favourable for the occurrence of thermal conditions oppressive to the human

Table 2. Synoptic situations types (Niedźwiedź 1981)

symbol	situation type	symbol	situation type
a – connected with anticyclonic conditions		c – connected with cyclonic conditions	
Na	Northerly flow	Nc	Northerly flow
NEa	North-easterly flow	NEc	North-easterly flow
Ea	Easterly flow	Ec	Easterly flow
SEa	South-easterly flow	SEc	South-easterly flow
Sa	Southerly flow	Sc	Southerly flow
SWa	South-westerly flow	SWc	South-westerly flow
Wa	Westerly flow	Wc	Westerly flow
NWa	North-westerly flow	NWc	North-westerly flow
Ca	central anticyclonic situation with no advection or centre of high pressure	Cc	central cyclonic situation with no advection or centre of low pressure
Ka	anticyclonic wedge with sometimes a few non-definite centres or unconstrained areas of higher pressure, axis of high pressure ridge	Bc	cyclonic trough or unconstrained area of low pressure, or axis of low pressure trough with various advection directions and system of fronts separating different air masses
X – col or undefined situations			

body, the calendar of synoptic situation types developed by Niedźwiedź for the Upper Vistula River Basin was used (pers. comm.). Niedźwiedź identified 21 types of synoptic situation based on direction of air mass advection and pressure systems, and marked them with a code consisting of the advection sector and the anticyclonic / cyclonic system index (Table 2).

Characteristic days

Annual course

Frosty days (i.e. days on which the air temperature falls below freezing at any point in the 24-hour period) are one of the most important planning factors in activities such as farming (particularly fruit farming), road maintenance, the construction business etc.

In the study area the average number of frosty days ranged from 70.7 in Tarnów to 105.8 in Zakopane. The occurrence of frosty days was more influenced by the location of the weather stations in the land relief than by altitude. Concave landforms, such as basins or valleys (Zakopane, Nowy Sącz and Kraków), favour their occurrence (Table 3).

The bulk of the occurrences were in winter (40) and spring (20), with just an isolated number of occurrences in summer. The greatest probability of frosty days was in March (13–19 days on average), while in July and August there were no occurrences at all.

One exception is the summit station at Kasprowy Wierch, where on average 80.0 frosty days a year were noted. This number is smaller than in Zakopane (105.8) and even in Kraków (82.3). This is connected with the location of the station high in the mountains and the occurrence of changes in patterns in the Western Carpathians. This area is characterized by a significant decrease in average monthly and annual temperature in relation to altitude. It is accompanied by significant increase in number of days with temperature <0˚C (freezing and severe freezing days). Consequently, thermal conditions in the high parts of mountains are more severe and stable (with lower fluctuations in temperature). This also means that along with an increase in altitude temperature falls below freezing less and less often. As a result at certain altitudes the number of frosty days decreases and their annual course also changes. Frosty days occur mostly between November and March in the foothills and in the lower parts of the mountains (Hess, 1965). At this time, on account of the very low temperature, they occur less

Table 3. Average annual, seasonal and monthly numbers of characteristic days in the period 1951–2000

Station	Months												Seasons				Year
	J	F	M	A	M	J	J	A	S	O	N	D	Spring	Summer	Autumn	Winter	
	frosty days ($t_{min} \leq 0^{\circ}C \wedge t_{max} > 0^{\circ}C$)																
K	13.8	13.5	16.2	7.0	0.7	-	-	-	0.3	5.6	11.2	14.1	23.9	-	17.0	41.4	82.3
T	12.5	11.8	14.1	6.1	0.6	-	-	-	0.1	4.0	8.9	12.6	20.8	-	13.0	36.9	70.7
A	12.7	12.2	13.4	7.4	0.8	-	-	-	0.1	3.8	9.7	12.8	21.6	-	13.6	37.6	72.8
NS	14.2	13.8	15.2	6.6	0.8	-	-	-	0.4	4.6	10.3	13.8	22.5	-	15.2	41.8	79.6
Z	14.7	14.2	18.4	13.3	2.7	0.1	-	-	1.4	10.6	15.4	14.9	34.5	0.1	27.3	43.9	105.8
KW	3.3	3.0	6.1	10.2	11.3	6.4	3.0	2.6	7.9	10.8	10.2	5.3	27.5	11.9	28.9	11.6	80.0
	days with $t_{min} \leq 0^{\circ}C$																
K	26.5	22.4	19.5	7.0	0.7	-	-	-	0.3	5.6	13.9	23.4	27.2	-	19.8	72.3	119.3
T	24.1	20.3	17.5	6.1	0.6	-	-	-	0.1	4.0	11.4	20.6	24.3	-	15.5	65.0	104.8
A	24.5	21.3	17.6	7.5	0.8	-	-	-	0.1	3.9	12.3	21.7	25.9	-	16.3	67.4	109.6
NS	24.2	20.5	17.5	6.6	0.8	-	-	-	0.4	4.6	12.4	20.9	24.8	-	17.3	65.6	107.8
Z	29.2	25.8	25.1	14.3	2.7	0.1	-	-	1.4	10.9	20.6	27.5	42.1	0.1	32.7	82.7	157.7
KW	30.4	27.9	30.2	25.3	15.6	7.2	3.0	2.7	10.4	17.8	26.7	30.2	71.0	12.8	55.0	88.5	227.4

Table 3. cont.

	freezing days (t_{max}<0°C)																
K	12.7	8.9	3.3	-	-	-	-	-	-	-	2.7	9.3	3.3	-	2.8	30.9	37.0
T	11.6	8.5	3.4	-	-	-	-	-	-	-	2.5	8.0	3.5	-	2.5	28.1	34.1
A	11.8	9.1	4.2	0.1	-	-	-	-	-	0.1	2.6	8.9	4.3	-	2.7	29.8	36.8
NS	10.0	6.7	2.3	-	-	-	-	-	-	-	2.1	7.1	2.3	-	2.1	23.8	28.2
Z	14.5	11.6	6.7	1.0	-	-	-	-	-	0.3	5.2	12.6	7.6	-	5.4	38.8	51.9
KW	27.1	24.9	24.1	15.1	4.3	0.8	-	0.1	2.5	7.0	16.5	24.9	43.5	0.9	26.1	76.9	147.4
	severe freezing days (t_{max}<-10°C)																
K	1.0	0.7	-	-	-	-	-	-	-	-	-	0.4	-	-	-	2.2	2.2
T	1.1	0.7	0.1	-	-	-	-	-	-	-	-	0.4	0.1	-	-	2.2	2.3
A	1.0	0.7	-	-	-	-	-	-	-	-	-	0.4	-	-	-	2.0	2.1
NS	0.7	0.4	-	-	-	-	-	-	-	-	-	0.4	-	-	-	1.5	1.6
Z	1.3	0.8	0.2	-	-	-	-	-	-	-	-	0.4	0.2	-	-	2.5	2.7
KW	5.2	5.4	2.9	0.2	-	-	-	-	-	0.1	1.2	3.4	3.1	-	1.3	13.9	18.4

K – Kraków, Z – Zakopane, T – Tarnów, KW – Kasprowy Wierch, A – Aleksandrowice, NS – Nowy Sącz
“ – “ t_{min} >0°C

often in higher parts of mountains, while, from May to October the highest number of frosty days are noted in the mountain summits. This is related to the increase of temperature in the lower parts of the mountains and temperature fluctuations around 0°C in high areas. Above 1800–1850 m a.s.l. frosty days can even occur in July and August (Hess 1965).

This is confirmed by figures for the occurrence of frosty days at Kasprowy Wierch, where the greatest incidence was in spring and autumn (27.5 and 28.9 days respectively) while the lowest was in summer and winter (11.9 and 11.6 days). This is also where frosty days were recorded in every month of the year, peaking in April, May, October and November (11 per month, on average).

Freezing and severe freezing days tend to occur in the cold half of the year and again can have an adverse effect on human activity. In contrast to frosty days, their occurrence is strongly influenced by altitude.

Typically, the number of freezing days is half the number of frosty days, and the average records show between 28.2 days in Nowy Sącz and 147.4 days at Kasprowy Wierch (Table 3). They occur mostly during the winter (20–30 days on average) and never in summer, with the notable exception of the sole summit station (Kasprowy Wierch averages 76.9 days in winter and 43.5 days in spring). January saw the highest number of freezing days (10–15 days on average), but they did not occur at all between May and September, again with the exception of isolated cases at Kasprowy Wierch even in July and August.

Only 2–3 severe freezing days (with a maximum temperature lower than -10°C) were recorded in the study area. The weather station at the summit of Kasprowy Wierch is again the sole exception, with ca. 18 days, including ca. 14 days during wintertime (mostly in January and February). At other stations severe freezing days occurred typically in winter and mostly in January.

Long-term variability

A look at the long-term variability in the number of characteristic days shows that while it differs from station to station, the general trends are similar (Fig. 2 and 3). This means that when, for instance, the number of frosty days rises at one station, higher numbers should also be expected at other stations. This is confirmed by high and statistically significant correlation coefficients (between the stations time series of the characteristic days) typi-

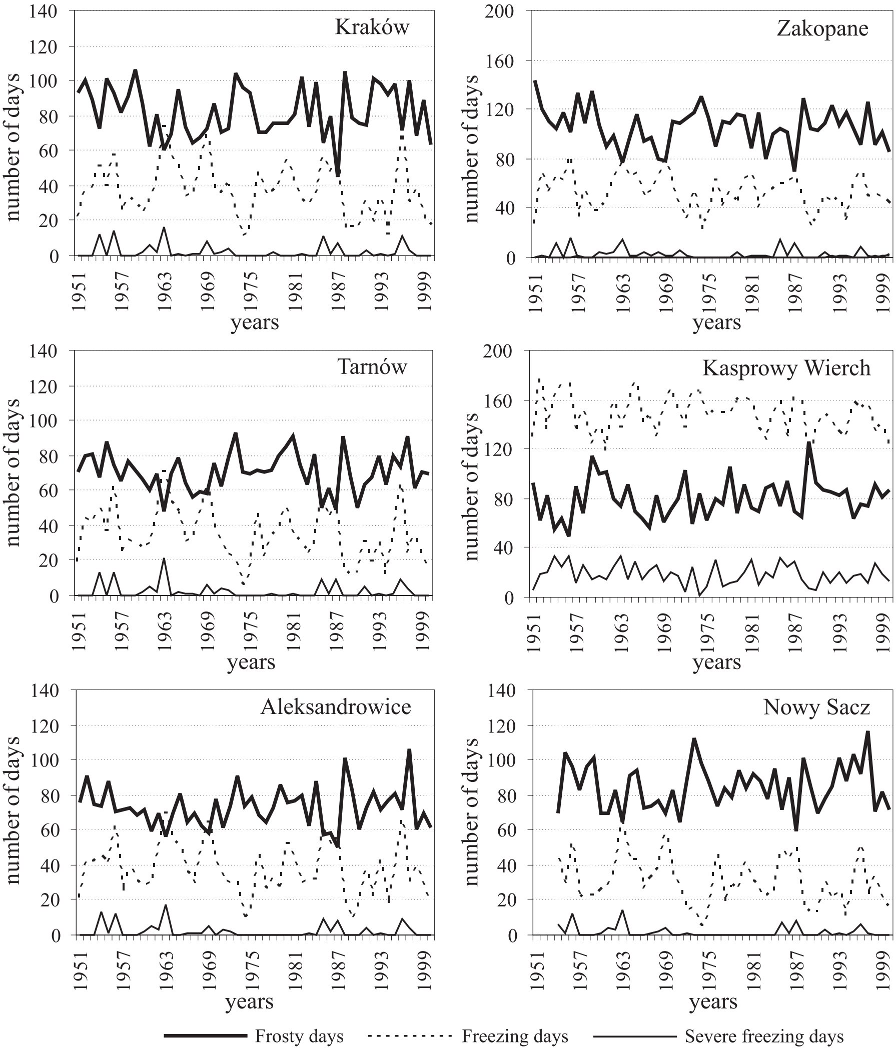

Fig. 2. Number of frosty, freezing and severe freezing days in the period 1951–2000 – presented separately for selected stations

cally exceeding 0.6 and often topping 0.9. Only the number of frosty days at Kasprowy Wierch stands out from the other stations, but this is accounted for by the station's high mountain weather profile.

The lowest annual number of frosty days (50) was recorded in Aleksandrowice (1987) and at Kasprowy Wierch (1956), while the greatest number

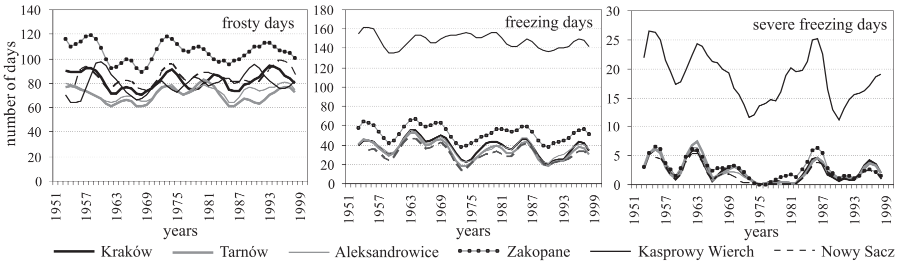

Fig. 3. Number of frosty, freezing and severe freezing days in the period 1951–2000

(144) occurred in Zakopane (1951). The range of variability of the number of frosty days at individual stations ranged from 45 days in Tarnów to 76 at Kasprowy Wierch. The highest variability ratio, however, may be noted at Kasprowy Wierch and Kraków, while the lowest was recorded at Zakopane.

Over the span of the study period, the variability of freezing and severe freezing days was greatest at Nowy Sącz and lowest at Kasprowy Wierch. The latter station recorded the highest numbers of freezing days (177 in 1952) and severe freezing days (34 in 1954 and 1963). The lowest number of freezing days occurred in Nowy Sącz (5 days in 1974), while there were numerous years without any days of severe freezing, ranging from 20 years in Zakopane to 31 years in Nowy Sącz. The greatest range of variability in the numbers of freezing and severe freezing days was recorded at Kasprowy Wierch (70 and 33 days), while in Zakopane (59 days) and Nowy Sącz (14 days) it was the lowest.

The long-term figures for days with various characteristics, plotted on Figures 2 and 3, reveal a single statistically significant trend (at $p<0.05$), i.e. a falling number of freezing days in Tarnów and in Nowy Sącz. None of the other variations can be considered statistically significant.

A closer investigation of periods with significantly greater or lower numbers of the various characteristic days revealed a coincidence in the same years at all stations, with the exception of frosty days. This would suggest that all but one type of characteristic days depend on macro-circulation rather than on the local conditions for their long-term modality. Only the spatial variability of the number of frosty days depends more on local conditions than on circulation factors.

The greatest numbers of freezing days were recorded at the beginning of the period and in the 1960s, with the lowest numbers in the mid-1970s and at the end of the 1980s and the beginning of the 1990s. Kasprowy Wierch, again, proved a slight exception to this pattern by recording the highest numbers of freezing days in the early 1950s and the lowest numbers towards the end of the decade and again at the end of the 1980s and the beginning of the 1990s. During the remaining part of the study period, Kasprowy Wierch recorded much lower variations than the other stations.

The long-term variability of the number of severe freezing days revealed four peak periods: the early 1950s, the first half of the 1960s, the second half of the 1980s and the late 1990s. From the beginning of the 1970s to ca. 1985 and again during the first half of the 1990s, very few such days were recorded at all.

Only frosty days break this consistent pattern with haphazard occurrence variations that show no apparent periods of higher or lower incidence over any continuous time period or across all stations. As a very general observation, frosty days occurred more frequently in the early and final years of the study period, as well as in the 1970s, while the largest drop in their incidence was observed during the 1960s.

An interesting pattern emerges from an analysis of the long-term variability of studied days in the form of a relatively ‘mild’ weather spell around the middle of the study period. This is when the weather stations recorded the lowest frequency of freezing, severe freezing and hot and very hot days (the analysis of which is beyond the parameters of the present study).

Comparison of the number of frosty and freezing days occurring in a particular year can be used as a good indicator of cool season severity.

In very cool years, a high number of freezing days was accompanied by small number of frosty ones, whereas frosty days predominated during mild winters. In summer, frosty days were mainly noted in high parts of the mountains. Their occurrence proves that thermal conditions during such summers are cooler in comparison with average ones, a fact also observed by Hess (1965). He also pointed out that in foothills and low parts of the mountains, the range of variability of the number of frosty days is much higher than in the summits.

Synoptic situations

At this stage the investigation focused on identifying the synoptic situations most favourable to the occurrence of each type of characteristic days. Anticyclonic situations prevailed overall, ranging on average from 50–60% on frosty days to 70–80% on freezing days. Certain differences were found between the seasons of the year and between individual stations, but such differences were only large at Kasprowy Wierch and in Zakopane.

In the present study, conditional probability was calculated in order to characterize the influence of synoptic situations on occurrence of thermally characteristic days. That index indicates the chance of occurrence of particular characteristic days providing that a particular synoptic situation prevails.

The relationship between frosty days and their synoptic situations seems to depend largely on the terrain where the weather station is located (Fig. 4). Outside the mountains at stations located in concave landforms (Kraków, Nowy Sącz) the spring and autumn frosty days occurred mostly at the time of advection from the southern sector (SEa, Sa, SWa), from the west, as well as during high-pressure centre and anticyclonic wedge situations (Wa, Ca, Ka). During the prevalence of these situations, the conditional probability of frost ranged typically between 30% and 51% in springtime and between 23% and 34% in autumn (Tables 4 and 6). Stations located on convex landforms (Tarnów, Aleksandrowice) mainly recorded Ea, SEa, Ca, Ka and NEc, as situations favourable for autumn frost, and yielded a conditional probability of 20–31%. In springtime the situations included Na, SEa, Wa, NWa, Ca and Ka (29–47%).

In early spring and late autumn, the synoptic situations mentioned above caused southerly and westerly advection of warmer air masses and as a result air temperature rose above 0ºC. In late spring and autumn non-advectional (Ca and Ka) and Na situations were of a great significance. Both Ca and Ka situations were accompanied by strong irradiation of energy at night and a decrease in temperature. The Na situation is connected with an inflow of very cool air form the north. In autumn, an inflow of cold air from the north-east favours the occurrence of frosty days over convex landforms.

In winter the Sa, SWa and Wa situations clearly favoured frost regardless of the landform location (conditional probability from 51% to 71%) (Table 5). Depending on the area, frosty days could also be favoured by such cyclonic situations as advection from the south and west, low pressure troughs and low pressure centre (SEc, Sc, SWc, Wc, NWc, Bc, Cc), with a condi-

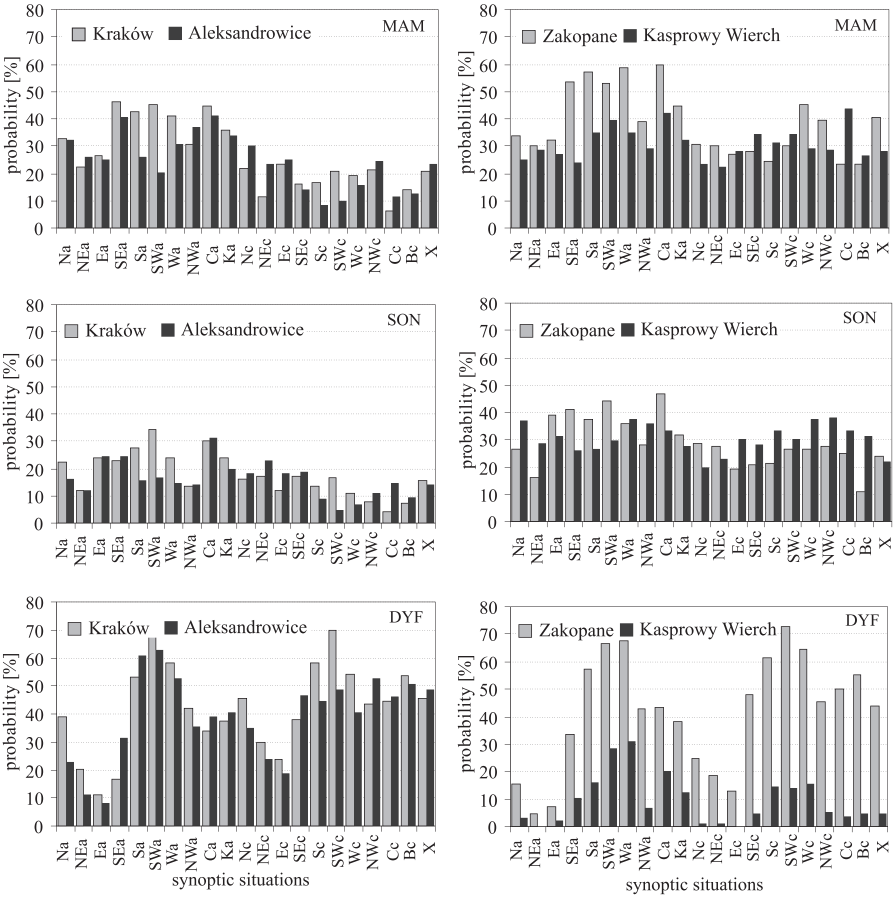

Fig. 4. Conditional probability of the occurrence of frosty days in synoptic situation types for selected stations in the period 1951–2000

tional probability higher than 40%, and up to 70% in Kraków (SWc). These situations are connected with an inflow of warmer air masses that lead to thawing weather. Frosty days in winter, in contrast to late spring and early summer, can be counted as rather "warm" days.

An inflow of very cold air from the eastern sector and the north under anticyclonic conditions is least favourable to the occurrence of frosty days. As a result, daily temperature remains below 0ºC in the circulation conditions mentioned above.

Table 4. Conditional probability (%) of the occurrence of frosty, freezing and severe freezing days for particular synoptic situations in autumn for the period 1951–2000

synoptic situations	frosty days ($t_{min} \leq 0°C \wedge t_{max} > 0°C$)						synoptic situations	freezing days ($t_{max} < 0°C$)						synoptic situations	severe freezing days ($t_{max} < -10°C$)					
	K	T	A	NS	Z	KW		K	T	A	NS	Z	KW		K	T	A	NS	Z	KW
Na	23	16	16	18	27	37	Na	5	7	10	5	17	54	Na	-	-	-	-	-	9
NEa	12	12	12	8	16	28	NEa	7	8	9	8	16	38	NEa	-	-	-	-	-	5
Ea	24	24	24	18	39	31	Ea	11	11	9	9	15	34	Ea	-	-	-	-	-	2
SEa	23	27	25	26	41	26	SEa	13	10	9	8	9	25	SEa	-	-	-	-	-	-
Sa	27	19	15	23	37	26	Sa	2	1	1	0	2	13	Sa	-	-	-	-	-	-
SWa	34	18	17	27	44	30	SWa	2	0	0	1	3	12	SWa	-	-	-	-	-	-
Wa	24	15	15	23	36	38	Wa	0	1	1	0	4	25	Wa	-	-	-	-	-	0
NWa	13	11	14	13	28	36	NWa	0	0	1	0	6	47	NWa	-	-	-	-	-	3
Ca	30	26	31	28	47	33	Ca	4	3	2	1	5	22	Ca	-	-	-	-	-	2
Ka	24	20	20	22	32	28	Ka	4	4	5	4	8	25	Ka	-	-	-	-	-	2
Nc	16	19	18	16	29	20	Nc	1	2	4	2	10	66	Nc	-	-	-	-	-	5
NEc	17	23	23	20	28	23	NEc	6	8	11	8	23	52	NEc	-	-	-	-	-	9
Ec	12	15	18	16	19	30	Ec	9	8	10	8	18	38	Ec	-	-	-	-	-	1
SEc	17	18	19	15	21	28	SEc	7	6	4	5	5	26	SEc	-	-	-	-	-	-
Sc	14	7	9	11	21	33	Sc	1	0	-	-	0	17	Sc	-	-	-	-	-	-
SWc	17	4	5	9	27	30	SWc	-	-	-	-	0	18	SWc	-	-	-	-	-	-
Wc	11	7	7	9	26	37	Wc	1	1	1	1	2	31	Wc	-	-	-	-	-	1
NWc	8	8	11	11	27	38	NWc	1	2	1	1	5	48	NWc	-	-	-	-	-	1
Cc	4	10	15	8	25	33	Cc	6	4	6	4	6	40	Cc	-	-	-	-	-	2
Bc	7	6	9	7	11	31	Bc	2	1	2	2	6	20	Bc	-	-	-	-	-	1
X	16	12	14	16	24	22	X	1	1	1	-	4	35	X	-	-	-	-	-	-

K – Kraków, Z – Zakopane, T – Tarnów, KW – Kasprowy Wierch., A – Aleksandrowice, NS – Nowy Sącz
" – " $t_{min} > 0°C$

Table 5. Conditional probability (%) of the occurrence of frosty, freezing and severe freezing days for particular synoptic situations in winter for the period 1951–2000

synoptic situations	frosty days ($t_{min} \leq 0°C \wedge t_{max} > 0°C$)					
	K	T	A	NS	Z	KW
Na	39	30	23	39	15	3
NEa	20	17	11	17	5	-
Ea	11	11	8	12	7	2
SEa	17	24	31	36	33	10
Sa	53	62	61	66	57	16
SWa	71	57	63	66	66	28
Wa	58	51	52	59	67	31
NWa	42	40	36	44	43	7
Ca	34	37	39	46	43	20
Ka	37	37	40	44	38	12
Nc	45	42	35	38	25	1
NEc	30	30	24	31	19	1
Ec	24	26	19	31	13	-
SEc	38	37	46	48	48	5
Sc	58	46	45	44	61	14
SWc	70	44	49	55	73	14
Wc	54	42	40	48	65	16
NWc	44	48	53	49	45	5
Cc	44	52	46	41	50	4
Bc	53	47	51	48	55	5
X	46	42	49	49	44	5

synoptic situations	freezing days ($t_{max} < 0°C$)					
	K	T	A	NS	Z	KW
Na	56	61	70	51	81	97
NEa	75	77	88	73	94	100
Ea	88	86	90	82	93	97
SEa	78	72	66	55	64	88
Sa	41	23	19	11	36	83
SWa	22	16	9	12	30	66
Wa	14	12	14	11	24	65
NWa	31	31	40	27	53	92
Ca	60	55	54	40	56	75
Ka	57	54	52	47	60	86
Nc	43	45	56	42	73	99
NEc	59	59	68	51	81	99
Ec	68	67	78	53	85	99
SEc	43	37	38	23	35	93
Sc	16	8	8	4	8	85
SWc	8	5	1	2	11	84
Wc	7	7	9	7	20	83
NWc	18	16	22	15	46	95
Cc	33	26	37	28	46	96
Bc	21	17	20	17	34	95
X	41	39	40	36	54	95

synoptic situations	severe freezing days ($t_{max} < -10°C$)					
	K	T	A	NS	Z	KW
Na	-	1	-	-	5	57
NEa	3	3	2	2	11	57
Ea	17	18	18	14	17	30
SEa	12	9	8	4	4	12
Sa	0	0	-	-	1	2
SWa	-	-	-	-	-	5
Wa	-	-	-	-	0	8
NWa	-	-	-	-	1	25
Ca	4	4	4	5	4	16
Ka	5	6	4	4	5	19
Nc	-	1	1	1	6	48
NEc	4	4	4	3	4	45
Ec	7	7	8	6	10	16
SEc	1	-	1	-	-	5
Sc	-	-	-	-	-	2
SWc	-	-	-	-	-	3
Wc	-	-	-	-	0	7
NWc	-	0	0	-	2	24
Cc	-	-	-	-	-	20
Bc	0	-	0	0	0	11
X	3	3	3	3	6	19

K – Kraków, Z – Zakopane, T – Tarnów, KW – Kasprowy Wierch., A – Aleksandrowice, NS – Nowy Sącz
“ – “ $t_{min} > 0°C$

Table 6. Conditional probability (%) of the occurrence of frosty, freezing and severe freezing days for particular synoptic situations in spring for the period 1951–2000

synoptic situations	frosty days ($t_{min} \le 0°C \wedge t_{max} > 0°C$)						synoptic situations	freezing days ($t_{max} < 0°C$)						synoptic situations	severe freezing days ($t_{max} < -10°C$)					
	K	T	A	NS	Z	KW		K	T	A	NS	Z	KW		K	T	A	NS	Z	KW
Na	33	33	32	28	34	25	Na	7	8	9	6	24	65	Na	-	1	1	1	1	16
NEa	22	26	26	20	30	28	NEa	7	6	7	5	16	54	NEa	-	0	-	-	2	8
Ea	27	28	25	31	32	27	Ea	13	13	16	11	21	46	Ea	0	0	0	-	0	6
SEa	46	47	41	51	53	24	SEa	7	7	8	2	8	43	SEa	-	-	-	-	-	2
Sa	43	31	26	38	57	35	Sa	-	1	1	1	1	36	Sa	-	-	-	-	-	1
SWa	45	24	20	37	53	39	SWa	-	-	-	-	1	30	SWa	-	-	-	-	-	1
Wa	41	29	31	38	59	35	Wa	-	1	1	-	4	57	Wa	-	-	-	-	-	1
NWa	31	31	37	30	39	29	NWa	5	5	5	3	17	67	NWa	-	-	-	-	-	7
Ca	45	42	41	34	60	42	Ca	1	-	-	-	1	36	Ca	-	-	-	-	-	-
Ka	36	32	34	35	45	32	Ka	2	3	3	2	8	45	Ka	-	-	-	-	0	4
Nc	22	22	30	21	31	23	Nc	6	7	10	5	22	68	Nc	-	-	-	-	-	9
NEc	11	20	24	15	30	22	NEc	6	5	7	4	13	57	NEc	-	-	-	-	-	5
Ec	23	23	25	22	27	28	Ec	12	13	15	8	20	51	Ec	-	-	-	-	1	3
SEc	16	14	14	12	28	34	SEc	5	6	4	2	4	29	SEc	-	-	-	-	-	-
Sc	17	10	8	13	24	31	Sc	1	0	1	-	1	31	Sc	-	-	-	-	-	0
SWc	21	10	10	15	30	34	SWc	-	0	-	-	0	37	SWc	-	-	-	-	-	0
Wc	19	16	16	19	45	29	Wc	0	0	0	-	2	57	Wc	-	-	-	-	-	1
NWc	21	18	24	20	40	29	NWc	2	2	5	1	9	64	NWc	-	-	-	-	-	6
Cc	6	5	11	7	23	44	Cc	2	1	3	1	2	42	Cc	-	-	-	-	-	1
Bc	14	10	12	11	23	27	Bc	0	0	1	-	2	35	Bc	-	-	-	-	-	1
X	21	20	24	26	41	28	X	3	3	4	2	6	50	X	-	-	-	-	-	4

K – Kraków, Z – Zakopane, T – Tarnów, KW – Kasprowy Wierch., A – Aleksandrowice, NS – Nowy Sącz
“ – “ $t_{min} > 0°C$

The influence of synoptic situations on the occurrence of frosty days in the mountains is slightly different. In Zakopane, located in a valley, spring and autumn frost still occurred primarily during anticyclonic situations, including SEa, Sa, SWa, Wa, Ca (with a springtime conditional probability of 53–60% and an autumn conditional probability of 36–47%) and Ka (45% and 32% respectively). Compared to the other stations, however, there is a significantly greater influence of air advection from the west and northwest linked to cyclonic situations (Wc, NWc). In winter, there is the distinct influence of advection from the south and west (Sa, SWa, Wa, Sc, SWc, Wc), as well as a low-pressure centre and cyclonic trough (Cc and Bc) (Fig. 4). In the situations listed the conditional probability often exceeds 50% by a large margin – up to 73% during SWc situations.

During the transitional seasons, the Kasprowy Wierch station has a flatter probability profile of frosty days in relation to the range of synoptic situations than do other stations. Indeed, the springtime conditional probability is roughly 20–30%, and it only drops by a few points in autumn. In springtime, three situations are favourable, i.e. SWa, Ca and Cc (39–44%), while in autumn these are Na, Wa, NWa, as well as Wc and NWc (36–38%). On account of the very low air temperature at that level, frosty days in winter are few and far between; they are most favoured by the advection of warm air masses from the west and southwest that accompanies an anticyclonic circulation and high pressure centres (Wa, SWa, Ca), where the conditional probability exceeds 20% (Tables 4–6).

Frosty days in summer occur only at Kasprowy Wierch and these are mostly favoured by Na, Wa, NWa, Nc and NWc (21–36%).

Synoptic situations favouring freezing days display much less difference between the stations (Fig. 5). Excluding Kasprowy Wierch, these days occur rarely (30–50 per year), mainly in wintertime and are favoured by long-lasting cooling and a dominance of cold air in the northern hemisphere. Thermal conditions can be made moderate or severe by particular synoptic types.

In the foothills of the Carpathians the springtime situations would include most of all the advection from the northern sector and from the east and southeast. The likelihood of freezing temperatures in such conditions ranges from 4% to ca. 16% outside the mountains and ca. 13–24% in Zakopane (Tables 4–6). In autumn, the most prominent favourable situations include Na, NEa, Ea, SEa (conditional probability up to ca. 13%; Zakopane up to 17%) and NEc, Ec, SEc and Cc (ca. 11% and 23% respectively). In the winter

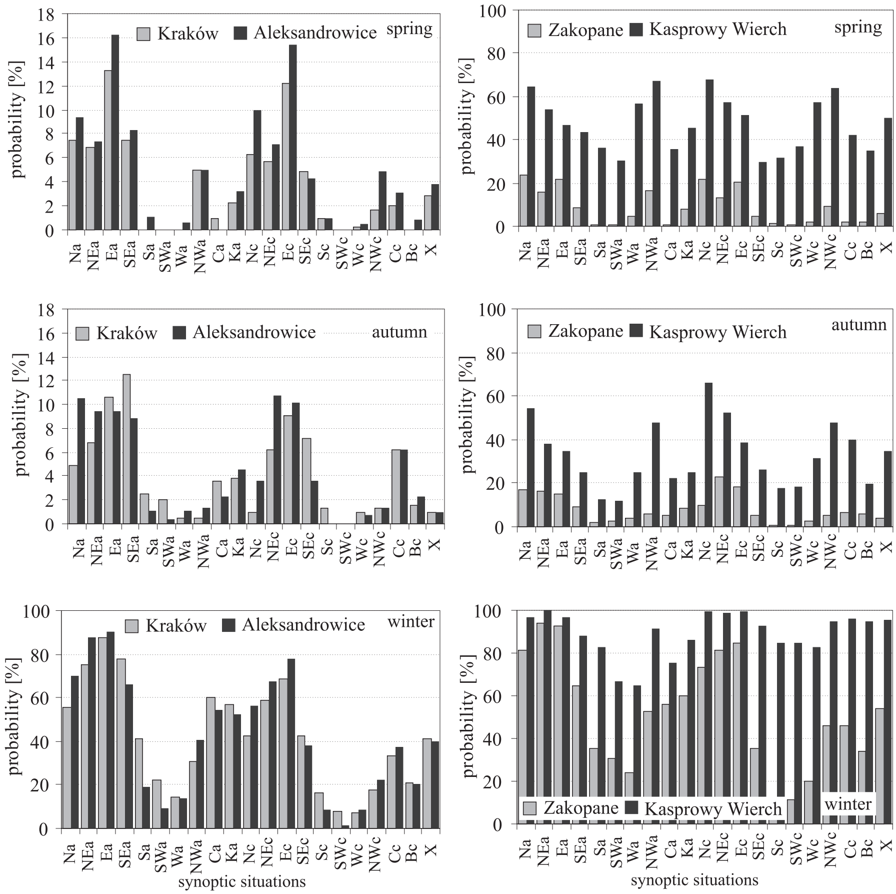

Fig. 5. Conditional probability of the occurrence of freezing days in synoptic situation types for selected stations in the period 1951–2000

season, freezing days are mostly favoured by advection from the north and northeast, from the east and southeast, as well as by the high pressure centres and the high pressure wedges (40–94%). On the other hand, the advection of considerably warmer air from the south, southeast and from the west is definitely unfavourable for the occurrence of freezing days in that region.

At Kasprowy Wierch in autumn, the highest likelihood of freezing days comes with the advection of cold air masses from the north and northwest and the NEc situation (47–65%). In spring freezing days are mostly favoured by advection from the north and northeast, from the west and northwest, as

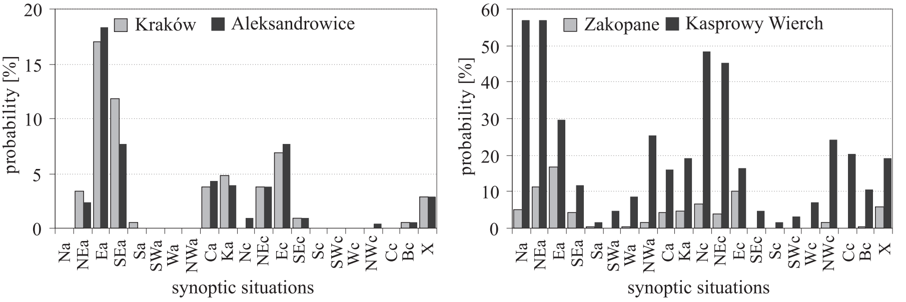

Fig. 6. Conditional probability of the occurrence of severe freezing days in winter in synoptic situation types for selected stations in the period 1951–2000

well as by Ec situation (51–68%). In winter, the probability figures typically exceed 80% by a large margin (Fig. 5, Tables 4–6).

An inflow of warmer air masses from the west and southwest as well as the center of high pressure (Ca) (65–74%) are recognized as being less favourable for the occurrence of freezing days. In the mountains, summer freezing temperatures appear during days with the advection of cool air from the north as well as at days with NWc and Cc situations, though these days are not frequently noted. Severe freezing days occur mostly in the winter season, with only isolated events recorded in March, except for Kasprowy Wierch, where these are also recorded in springtime and autumn. In these seasons, the most favourable situations for the occurrence of severe freezing days included anticyclonic situations with the advection of very cool air from the north, northeast and east, while such situations in Zakopane also included the eastern cyclonic and high pressure wedge (Ec and Ka) (Fig. 6, Tables 4–6).

In winter, severe freezing days are most favoured by advection from the east (Ea, ca. 13–18% and Ec, ca. 6–10%), and in Kraków, Tarnów and Aleksandrowice also by the south-eastern anticyclonic situation (SEa, 7–12%) bringing very cool air from continent.

At Kasprowy Wierch the picture was quite different, as the favourable situations included primarily advection from the north and northwest, with the related conditional probability amounting to ca. 45–57% (Fig. 6, Tables 4–6). The same set of situations should also be regarded as favouring very low temperatures in autumn. In springtime, these include advection from the northwest and the eastern anticyclonic situation (NWa, NWc, Ea).

Conclusions

The results permit the conclusion that despite its highly diverse geographic environment the thermal conditions of Małopolska are relatively consistent, are strongly dependent on general atmospheric circulation and are only minimally influenced by local conditions.

In terms of thermal conditions which may be oppressive for humans Zakopane and Kasprowy Wierch were found to be the most notable a fact explained by the geographical location of the two sites. The Tatra summit recorded a number of freezing days many times greater than elsewhere. The greatest number of frosty days occurred in the Zakopiańska Basin, a trench-like formation at the foot of the Tatras where the town of Zakopane is located.

In Małopolska every year, on average, there are between 70 and 100 frosty days and 30–50 freezing days, with the latter number rising to ca. 150 at Kasprowy Wierch. Severe freezing days are much scarcer, amounting to only 2–3 per annum, with the exception of the high Tatra Mountains with typically ca. 18 days p.a.

The long-term variability of the characteristic days examined revealed consistencies between stations in terms of the overall pattern, but to greatly varying degrees. Exceptions to this pattern included frosty days – which formed a different picture altogether – and records from Zakopane and Kasprowy Wierch in contrast with the other stations.

There are no significant trends in the long-term course of the days with particular thermal characteristics, though a slight decrease in their number can be noticed. The only long-term trend that was found to be statistically significant involved a decrease in the number of freezing days in Tarnów and Nowy Sącz (at $p<0.05$).

A decrease in the number of days under consideration was also noted at other weather stations in Poland (Limanówka 1999; Kaszewski et al. 2007). These tendencies were the most clear in the period 1792–2002 in Krakow in wintertime (Piotrowicz 2002/2003). In the period starting from the 1950s of 20th century, the number of freezing and severe freezing days in Kraków were distinct lower than the average. The changes described above are related to global temperature increases that are particularly noticeable in winter.

Most of the characteristic days studied occurred during the prevalence of anticyclonic synoptic situations. Frosty days are mainly favoured by advection from the southern sector and from the west during anticyclonic systems; cyclonic systems are also favourable in wintertime. Freezing days are most likely during advection from the east, southeast and the northern sector. Severe freezing days are mostly favoured by advection from the east, especially during anticyclonic systems. High-pressure centre or wedge situations also favour the occurrence of any of the characteristic days studied. The station at Kasprowy Wierch is an exception, however, with advection from the northern sector and from the west also playing a favourable role.

The results of previous research by Niedźwiedź (1987) also proved the significant role of anticyclonic situations in the occurrence of the characteristic days analysed. In Kraków the occurrence of springtime frosty days (radiative-advectional origin) is favoured by the advection of Arctic air masses from both the east and southeast whereas the occurrence of autumn frosty days is connected with an inflow of air from the west and northwest.

Future research might well focus on examining the types of synoptic situations which preceded the characteristic days under consideration, along with the impact of cloudiness on the occurrence of the days examined. As it appears from the studies by Kossowska-Cezak (1987), days with a high amplitude of temperature were accompanied by distinct change in the advection of the air masses. On such days air temperature usually fell below freezing. Such changes of temperature are sometimes not simultaneous with changes in atmospheric circulation but they are usually delayed for 1–2 days. Kossowska-Cezak also notes the significant role played by cloudiness on successive days. An increase in cloudiness happening after anticyclonic activity favours a rise in minimum temperature.

It would also be interesting to analyse the relationship between the long-term variability of the occurrence of thermal characteristic days and the variability of synoptic situations as well as the character of air masses. This aspect seems to be interesting in the context of the rising frequency of the occurrence of Arctic air masses over Southern Poland or in the context of variability in frequency of Polar air masses, both maritime and continental (Niedźwiedź 2000b, 2003).

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